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Structural safety and failure modes in Gothic vaulting systems

Dimitris THEODOSSOPOULOS¹, and Braj SINHA²

ABSTRACT

Aspects of the pathology of Gothic vaults as a result of lateral instability are discussed in this paper. Damage due to the dominant action of supports spread caused as a result of disastrous interventions, or inefficient or too ambitious faulty designs is examined. The paper aims to collect data and failure patterns already available through various sources in the technical literature and discuss them into a coherent format, establishing service and failure limits of deformations.

KEYWORDS

Gothic architecture, vaults, structural safety, structural design, stone masonry

1 INTRODUCTION

Stone masonry vaults formed an integral part of the structural system of Gothic churches. In the quest for wider window openings and more slender structure, the gothic masons developed a structural system in which the main elements (arches, vaults, slender piers, walls) acted together to provide the dynamic equilibrium. The dominant pathology of the vaults in this scheme occurs when this dynamic equilibrium is disturbed by either failure of the supports or instability of the lateral elevation.

The failure occurs when a number of hinges develop that are sufficient in transforming the vault into a mechanism and the relevant pattern becomes theoretically important. Although extensive conservation of Gothic buildings has taken place, the number of surveys published or structurally interpreted with modern methods is too limited in order to safely define a pattern. The available information is often very variable and the quality or coverage of the case studies is not uniform.

This study reviews the literature on the range of pathologies observed in Gothic vaulting systems (papers and reports on structural condition). Interpretation of the origin and propagation of failure is attempted by structural analysis of representative cases. The structural actions studied are those that cause the predominant lateral instability of the vaults. The discussion of less usual actions like wartime shelling gives further useful insight on the behaviour of specific areas of vaults affected by this highly localised damage.

2 FAILURE PATTERN DUE TO LATERAL INSTABILITY

Lateral instability is the predominant source of failure in Gothic churches and often results from design errors, erroneous interventions or neglect. If typical cross sections are considered to represent the transverse behaviour of naves, its pathology (Fig. 1) is mainly triggered by failing flying buttresses or excessive increase of vault thrusts against the buttresses. The vaults are affected by the spread of their supports (outwards at the upper portion, inwards at the aisles) producing crack that can be summarised in Fig. 2: usually a hinge line forms along the intrados with a transverse detachment following at the wall edge and abutments. The progressive failure of the vault is further accelerated by the instability of the elevation due to its slenderness.

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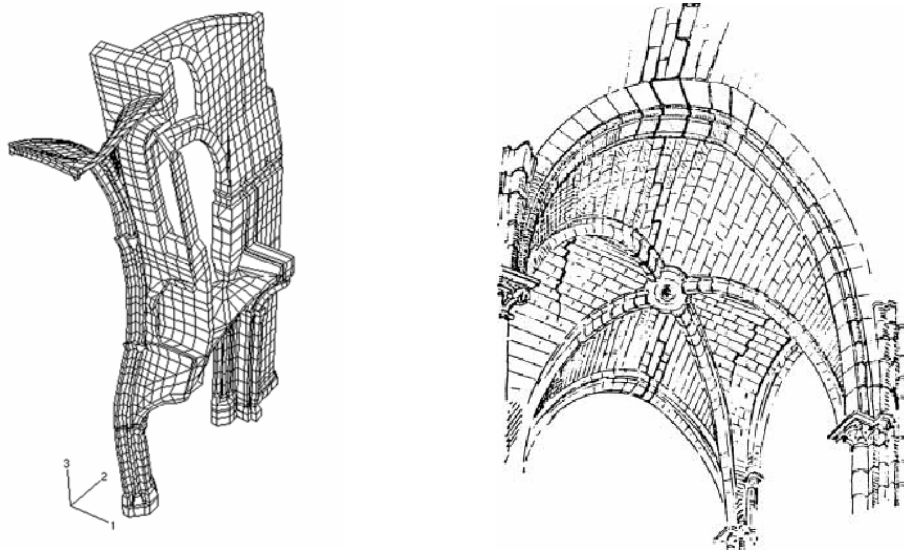


Figure 1. Deformation patterns in Gothic buildings: left, Burgos Cathedral FE model, magnified 200 times [Theodossopoulos 2004]; right, typical crack pattern established by Pol Abraham [Heyman 1995]



Figure 2. Crack patterns in the high vaults of Lincoln and Amiens Cathedrals

It is natural to expect that structures of this age could develop weakness in the lateral supports either due to creep deformation of the buttressing masonry or insufficient balance of the loads of the vaults as a result of limited knowledge. Some aspects of service conditions such as typical longitudinal cracks at the high vaults are illustrated in Fig. 2. Table 1 presents values of lateral displacements u as observed in churches that have deformed but are not in a collapse condition. This condition can be considered as the safety limit and Table 1 shows this can be 1/100 of the transverse span s .

Table 1. Lateral spread of supports within service observed in Gothic churches

| Case | Location | Spread u (mm) | Span s (m) | u / s | Source |
|----------------------|-------------------------------|--------------------|-----------------|---------|------------------------|
| Amiens Cathedral | SE crossing pier | 125 | 12.45 | 1/100 | [Bilson 1906] |
| Notre Dame, Paris | Nave | 305 | 14 | 1/46 | [Bilson 1906] |
| Durham Cathedral | Nave, 2 nd pier, N | 121 | 11.22 | 1/93 | [Bilson 1915] |
| Durham Cathedral | Nave, 6 th pier, S | 102 | 11.22 | 1/110 | [Bilson 1915] |
| Lincoln Cathedral | Nave | 75 | 12.7 | 1/170 | [Bailey 1996] |
| St. Martin, Landshut | | 116 | 11.6 | 1/100 | [Jagfeld 2000] |
| Burgos Cathedral | FE model, nave | 2 | 11 | | [Theodossopoulos 2004] |

There is a range of such crack patterns and displacements that are historic or chronic defects, usually developed soon after the construction of the vaults, and no movement was reported any more. For example, the outward lean of the nave of Durham Cathedral was recorded at various points at the clerestory string course level during strengthening works in 1915 [Bilson 1915, Curry 1981]. The deformation was attributed to the weakness of the

early buttressing system that was formed by quadrant arches added principally to provide support to the roof of the triforium rather than bracing the thrusts of the high vaults. No further movement or cracks have been recorded since. It also has to be noted that the original vaults of the choir were replaced in 1235 after dangerous cracks appeared. It can be argued therefore that the nave vaults constitute an improvement to the original design, as the lean is not significant.

The FE model of Burgos Cathedral (Fig. 1) indicates a similar location of maximum displacement, although the value is much lower (2 mm). The difference is due not only to the fact that a linear elastic analysis was performed that ignored creep or settlements but also to the presence of more efficiently designed buttressing.

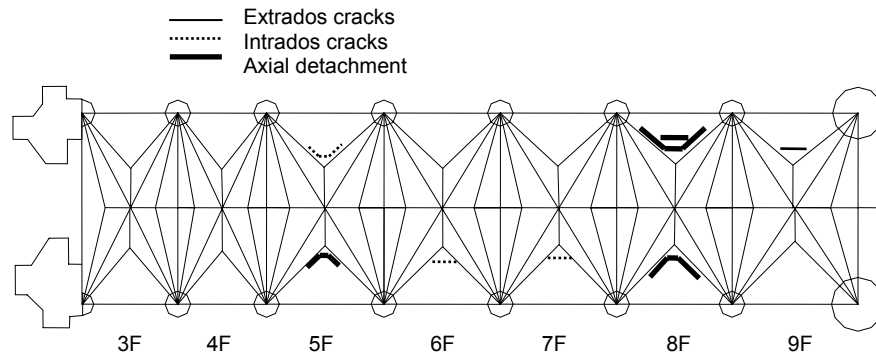


Figure 3. Crack pattern, nave of Lincoln Cathedral (after Bailey 1996)

In Lincoln Cathedral the crack pattern in Figs 2 and 3 can be seen today. Especially at bay 8F there is a strong detachment of the fabric from the tierceron ribs and fragments of plaster have also fallen (Fig. 2). However, the out-of-plumb of the outer wall is within reasonable limits (Table 1). Timber edge beams have been placed at the North side of the nave wall between bays 4F and 7F indicating a local weakness [Bailey 1996] that is probably the origin of these cracks. This pattern is often encountered in major scale cathedrals: cracks initiate at the intrados parallel to the longitudinal vertex followed by extrados cracks above the springings, forming ultimately a 3-hinge mechanism that leads to collapse. Laboratory tests [Ortolani 1988, Theodossopoulos et al 2002] and FE analysis on case studies both have verified this pattern, as will be seen in later sections.

3. FAILURE DUE TO DESIGN ERRORS

Most of the heavily deformed or failing gothic churches (Table 2) are the result of errors in the design or later inadequate alterations or interventions, and they are dealt with in this section.

Table 2. Values of lateral spread of supports close to collapse

| Case | Location | Spread u (mm) | Span s (m) | u/s | Source |
|-----------------------|-------------------|--------------------|-----------------|-------|------------------------|
| Vitoria Cathedral | | 174 | 9.24 | 1/53 | [Azkarate 2001] |
| <i>Id</i> | | 120 | 5.5 | 1/46 | <i>id</i> |
| Beverley Minster | Aisle, S transept | - | | 1/19 | [Bilson 1906] |
| Blyth Church, Notts | Aisle | - | | 1/13 | [Bilson 1906] |
| Kloster Maulbronn | Dormitory | 170 | 4.50 | 1/26 | [Jagfeld 2000] |
| León cathedral | Nave | 150 | 7.5 | 1/50 | [Martínez 2000] |
| Holyrood Abbey | N aisle | 75 | 3.77 | 1/50 | [Mylne 1766] |
| Holyrood model | S aisle | 30 | 0.96 | 1/33 | [Theodossopoulos 2002] |
| Holyrood FE model | S aisle | 96 | 3.77 | 1/40 | [Theodossopoulos 2003] |
| S. Angelo vault model | Nave | 260 | 7.36 | 1/28 | [Ceraadini 1996] |

Two classic examples where errors in the design had almost a catastrophic effect are Beauvais and Vitoria cathedrals. The partial collapse of the extremely slender piers in the former in November 1284 and the excessive deformations that can be still observed today [Taupin 1993] traditionally highlight the limits in the proportions a Gothic church could reach (Fig. 4). Various hypotheses on what triggered the collapse have been put forward by S. Murray [1989] or J. Heyman [1995], like the configuration of the porte-a-faux junction of the upper structure towards the aisles or the location of the flying buttresses. The very slender design is still subject to accelerating deformations and vibrations today that have to be constantly monitored at three levels across the building.

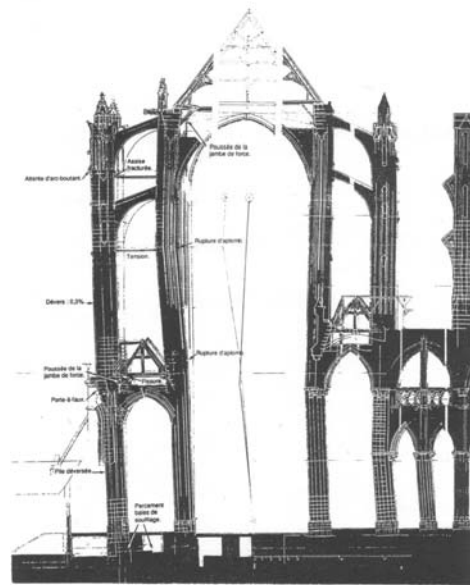


Figure 4. Horizontal displacement in the North transept of Beauvais Cathedral [Taupin 1993]

Vitoria Cathedral clearly illustrates a typical problem of Gothic architecture, i.e. the addition of flying buttresses after significant lateral deformations have developed. In this case even such a remedy was not enough and a series of arches were built in the nave above the ridge line of the aisle vaults. Only recently, a comprehensive programme of interventions was developed to strengthen the fabric and in that occasion the movement of the church was carefully monitored (Fig. 5). The distorted configuration of the elevation corresponds clearly to the pattern expected due to insufficient containment of the upper thrusts and eventually deformations of this scale were impossible to cancel even if strengthening of the buttressing was applied.

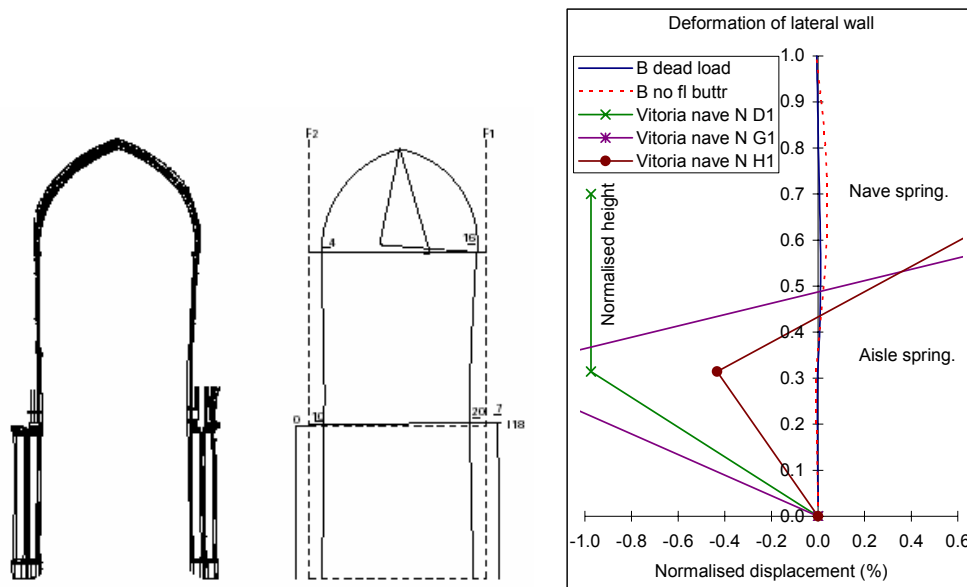


Figure 5. Deformed lateral elevation of Vitoria Cathedral [Azkarate 2001] and comparison of the lateral displacement of Vitoria and Burgos Cathedral, normalised against the span

Figure 6 reports the crack pattern in Kloster Maulbronn due to the instability of the outer walls. The Dormitory is a single story building, without upper structures and the observed deformation indicates clearly the sensitivity of cross vaults to the conditions of their supports. Several German case studies are discussed by Jagfeld [2000].

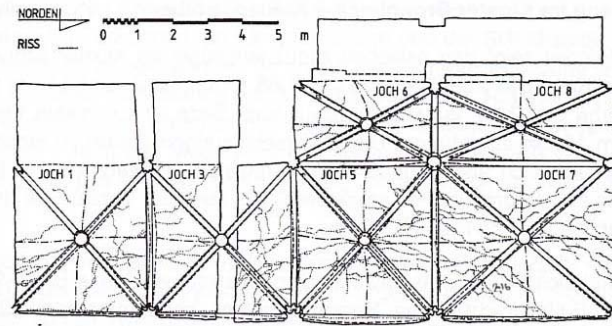


Figure 6. Crack pattern at the Dormitory in Kloster Maulbronn [Jagfeld 2000]

Evidence of inefficient designs is often available from historic or archaeological sources. The early choir of Durham Cathedral is the area where the revolutionary ribbed vaults were first applied in a large scale in 1103. Safety precautions or stylistic renovation (linked to the new Chapel of the Nine Altars) required these vaults to be replaced with pointed ones in 1253.

4. THE EFFECT OF INAPPROPRIATE INTERVENTIONS

Disastrous interventions on already damaged fabric are another usual source of failure in vaults. The Holyrood Abbey church in Edinburgh failed on December 1768 after a replacement of the roof with heavy diaphragm walls and stone flags causing a huge increase in weight and thrusts that the insufficiently maintained buttresses could not contain [Theodossopoulos 2003]. The architect W. Mylne surveyed the church shortly before collapse and reported a highly visible deformation pattern, similar to Fig. 1 (data in Table 2).

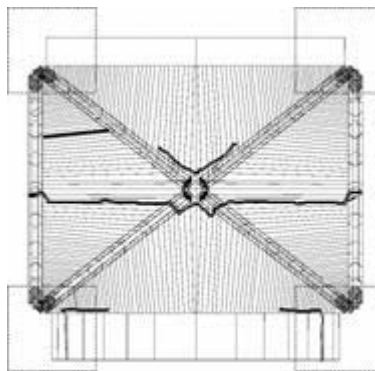


Figure 7. Experimental crack pattern in a model simulating the aisle vaults of Holyrood Abbey Church [Theodossopoulos et al 2002]

An experimental study of the church collapse [Theodossopoulos et al 2002] verified the values and gave useful insight to the development of the cracks that transform the structure into a mechanism (Fig. 7). The study concentrated on the aisle vaults and the typical longitudinal cracks and detachment of the vault from the back ribs were initially observed. Next, hinges formed above the springing, accompanied by detachment of the back web from the wall, confirming the development of the so-called Sabouret's cracks in the areas of rigid supports [Heyman 1995]. Failure of the vault occurred at 30 mm movement, although the structure did not collapse as a result of interlocking of the webs with the ribs.

5. ANALYTICAL MODELLING AS A SOURCE OF INFORMATION

Structural interpretation of the origin and propagation of failure was also attempted using structural analysis of major early English cathedrals (Durham, Lincoln, Wells, Canterbury), simulating the geometric instability as a movement of the supports and using a biaxial failure criterion for the stone masonry, as developed in the case of Holyrood [Theodossopoulos 2008]. The typical failure pattern that developed in most cases is illustrated by Durham in Fig. 8 and the values of the support spread are reported in Table 3. The FE models show good agreement with the in-situ observed patterns, and they can also provide information on the rate of failure: in most cases the first cracks appeared above the supports, followed by cracks along the longitudinal ridge.

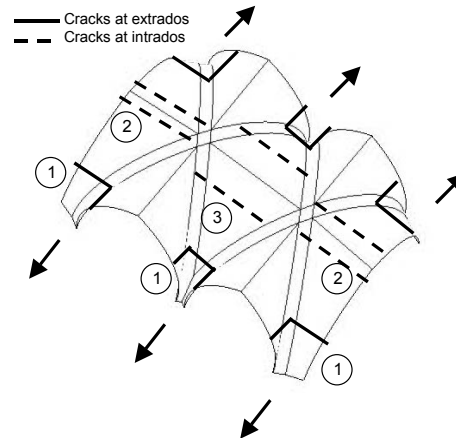


Figure 8. Crack pattern from the FE model of Durham Cathedral choir vaults at a supports spread of 330 mm [Theodossopoulos 2008]

Table 3. Analytical assessment using FE models

| Case | Location | Spread u (mm) | Span s (m) | u / s | Source |
|----------------------|-----------------|--------------------|-----------------|---------|------------------------|
| Durham Cathedral | Nave | 330 | 11.22 | 1/34 | [Theodossopoulos 2008] |
| Canterbury Cathedral | Choir | 670 | 13.1 | 1/20 | [Theodossopoulos 2008] |
| Wells Cathedral | Choir | 275 | 9.64 | 1/36 | [Theodossopoulos 2008] |
| Lincoln Cathedral | Nave, tierceron | 503 | 12.5 | 1/25 | [Theodossopoulos 2008] |
| León cathedral | Nave | 100 | 7.5 | 1/75 | [Martinez et al 2000] |
| FE model | | 404 | 10 | 1/25 | [Jagfeld 2000] |

6. EARTHQUAKES

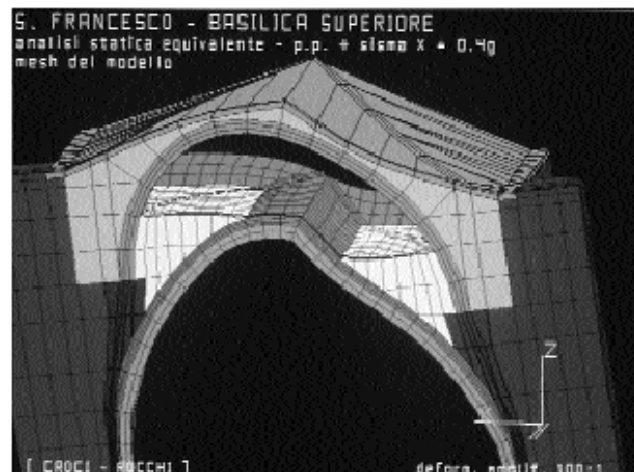


Figure 9. High deformation of a vault from St. Francis Basilica [Crocì 1998]

The well documented collapse of two vaults at St. Francis Basilica in Assisi in September 1997 has been supported by extensive 3D FE modelling that was used for the interpretation of the collapse and the design of the strengthening interventions [Crocì 1998]. The study confirmed that excessive volumes of the loose spandrel fill were able to shift during the acceleration and load non-uniformly the shell, increasing the tensile stress close to the vertices of the vault and causing unrecoverable curvature inversions (Fig. 9). Considering various structural schemes for the collaboration between the ribs and the shells and the action of the spandrel fill, the collapse was attributed to rather inherent incapacity of gothic vaulted structures to withstand lateral actions that disturb its intuitively conceived almost form-active geometry. In another case, the collapse of the Cathedral of Sant'Angelo dei Lombardi after the 1980 earthquake of Irpinia, Italy (Fig. 10) illustrates the similarity of the damage pattern caused by the transverse component of the seismic action to that of the imposed deformations reported earlier.

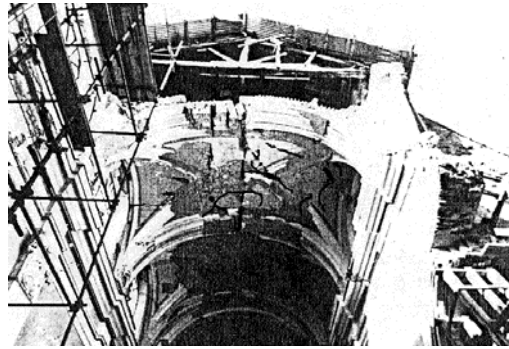


Figure 10. Crack pattern at the nave of Sant'Angelo dei Lombardi Cathedral [Giuffré 1988]

In terms of numerical simulation and understanding of the problem, P. Lourenço applied a non-linear material and geometric analysis to the vaults of the Church of Christ in Outeiro, Portugal, to assess the origin of their damages [Lourenço 1999]. The dynamic loads were simulated as equivalent, quasi-static horizontal loads, added to the permanent dead load of the structure. Assuming a simplified linear elastic law for the material, the vault was modelled with shell elements for the webs and beams for the ribs and arches. The analysis made evident the inadequate design of the vaults, as the thrusts from either the vertical or the horizontal loads could not be sustained by the columns and the insufficient joint between the shell and the web. Moreover, the stiffness of the nave arch proved to be inappropriate. Although the FE model underestimated the magnitude of deformations recorded in the survey of the building, the strain patterns and the magnitudes yielded by the model were sufficient to explain the origin of the failure.

8. ACTIONS AFFECTING SPECIFIC AREAS OF THE FABRIC

Other sources of failure include accidental loadings like shelling of Rheims, Soissons, Noyon cathedrals during warfare in 1915 [Gilman 1920], sharp changes in the water table (York Minster) etc. Shell fire damages on the upper structure can have an immediate effect to the rest of the structure as a sudden loss of equilibrium of the lateral wall. It was however the direct hits from shelling during the First World War that, apart from the shocking effect on the population, not only made clear the dynamic equilibrium of the parts but also revealed some fundamental aspects of the relationship between the masonry shell and the ribs in the behaviour of a vault.

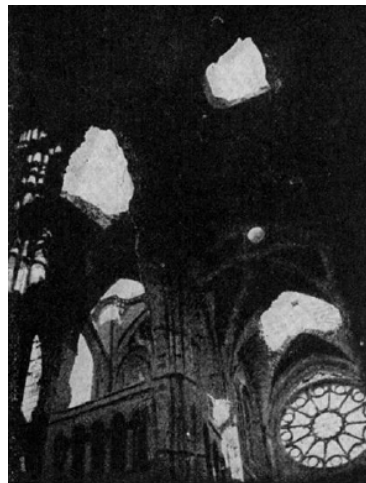


Figure 11. Shell holes in the vaults of Rheims Cathedral [Gilman 1920]

As expected, such structures have a high degree of redundancies, when compared to modern concrete shells. It is interesting however to observe that the rib actually functions as a reinforcement to the vault. The localised damage shows that ribs being built within the masonry provide relatively substantial stiffness at the adjacent areas, resulting in a solid abutment rather than a subtle reinforcement against excessive bending, as some contemporaries viewed it. This behaviour became also obvious in the failure development as monitored at the Holyrood Abbey experiments, where a hinge formed above the stiffer area of the springing (tas-de-charge).

9. SUMMARY

The experimental and numerical analysis discussed briefly can show that a displacement of the supports by 1/30 of the span can be defined as the serviceability limit after which the cracks cause the geometric instability of the vault. The discussion of data from the literature survey and the structural analysis can form the basis for the assessment of the safety of gothic cross vaults.

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